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Analysis of the Impact of Urban Green Spaces on Mitigating the Urban Heat Island Effect

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Abstract

The Urban Heat Island (UHI) effect, characterized by higher temperatures in urban areas compared to their rural surroundings, poses significant challenges for energy consumption, air quality, and public health. This study examines the impact of urban green spaces on mitigating the UHI effect in four major Spanish cities: Madrid, Barcelona, Seville, and Valencia. Using high-resolution satellite imagery, ground-based temperature measurements, and advanced GIS and statistical modeling techniques, we quantified the temperature differences between green and non-green urban areas. Our findings indicate that green spaces, including parks, street trees, and green roofs, significantly reduce urban temperatures, with parks exhibiting the highest cooling effects. The spatial analysis revealed that UHI hotspots are concentrated in densely built-up areas, while green spaces effectively mitigate these effects. Seasonal variations show that the cooling benefits of green spaces are more pronounced during the summer months. This study highlights the importance of incorporating diverse and well-distributed green spaces in urban planning to enhance thermal comfort, reduce energy consumption, and improve urban livability. Policy recommendations are provided to guide the integration of green infrastructure in climate adaptation strategies for Spanish cities.

Keywords: Urban Heat Island (UHI), urban green spaces, temperature mitigation, climate adaptation

1. Introduction

1.1 Background on the Urban Heat Island (UHI) Effect

The Urban Heat Island (UHI) effect is a well-documented phenomenon where urban areas experience higher temperatures than their rural surroundings due to human activities and infrastructure. This effect is primarily caused by the replacement of natural land cover with impervious surfaces such as buildings, roads, and other infrastructure that absorb and retain heat. Additionally, the high concentration of energy consumption in urban areas, including vehicular emissions, industrial activities, and air conditioning, further exacerbates this temperature increase. The UHI effect has significant implications for energy consumption, air quality, and public health, particularly during heatwaves.

1.2 Overview of Urbanization Trends in Spain

Spain, like many other countries, has experienced rapid urbanization over the past few decades. According to data from the National Institute of Statistics (INE), the proportion of the Spanish population living in urban areas increased from 60% in 1960 to over 80% by 2020. This rapid urbanization has led to increased construction of buildings, roads, and other infrastructure, contributing to the UHI effect in major Spanish cities such as Madrid, Barcelona, and Seville. The densification of urban areas, coupled with a reduction in natural green spaces, has further intensified this phenomenon.

1.3 Importance of Studying UHI in the Context of Climate Change

Climate change is projected to increase the frequency, duration, and intensity of heatwaves, making the UHI effect an even more pressing concern for urban areas. Elevated temperatures due to UHI can exacerbate the health impacts of heatwaves, increase energy demand for cooling, and deteriorate air quality by increasing the formation of ground-level ozone. Understanding the UHI effect and developing effective mitigation strategies is crucial for enhancing urban resilience to climate change, improving public health outcomes, and reducing energy consumption. In this context, urban green spaces have emerged as a key strategy for mitigating the UHI effect.

1.4 Objectives of the Study

This study aims to analyze the impact of urban green spaces on mitigating the UHI effect in Spain. Specifically, the objectives are to:

1) Quantify the temperature differences between green and non-green urban areas.
2) Assess the spatial distribution of UHI in selected Spanish cities.
3) Evaluate the effectiveness of different types of urban green spaces, such as parks, street trees, and green roofs, in reducing urban temperatures.
4) Provide policy recommendations for urban planners and policymakers to enhance the role of green spaces in mitigating UHI.

By investigating the role of urban green spaces in mitigating the UHI effect in Spain, this study aims to contribute to the development of more sustainable and resilient urban environments. The findings are expected to inform urban planning practices and policy decisions, helping to create cooler, healthier, and more livable cities in the face of ongoing climate change.

2. Literature Review

The Urban Heat Island (UHI) effect is a widely studied phenomenon characterized by higher temperatures in urban areas compared to their rural surroundings. This temperature disparity is attributed to the extensive use of impervious surfaces such as concrete and asphalt, which absorb and retain heat. Additionally, the high density of buildings, reduced vegetation, and anthropogenic heat sources like vehicles and industrial activities contribute to the UHI effect. Studies have shown that the UHI effect can increase urban temperatures by several degrees Celsius, particularly during the night. For example, Oke (1982) demonstrated that urban areas could be up to 12°C warmer than their rural counterparts during the night in some cities. The intensity of UHI varies with factors such as city size, population density, and local climate conditions (Santamouris, 2015). Research has also indicated that the UHI effect can exacerbate heatwaves, posing significant risks to public health, energy consumption, and overall urban livability.

Urban green spaces, including parks, street trees, green roofs, and urban forests, have been identified as effective strategies for mitigating the UHI effect. Green spaces help cool urban areas through various mechanisms, such as shading, evapotranspiration, and the cooling effects of vegetation. Shading provided by trees and vegetation reduces the amount of solar radiation absorbed by buildings and pavements, thereby lowering surface and air temperatures. Evapotranspiration, the process by which plants release water vapor into the air, also contributes to cooling. A study by Bowler et al. (2010) found that urban parks could reduce temperatures by up to 1.9°C, with larger and more vegetated parks having a greater cooling effect. Furthermore, green roofs, which involve the installation of vegetation on building rooftops, have been shown to reduce rooftop temperatures by up to 40°C compared to conventional roofs (Liu & Bass, 2005). Street trees can also lower temperatures along urban streets, improving thermal comfort for pedestrians and reducing the need for air conditioning in adjacent buildings (Armson, Stringer, & Ennos, 2012).

Research on the impact of urban green spaces on the UHI effect has been conducted in various countries, providing valuable insights and comparative data. For instance, a study in New York City found that green roofs could reduce peak summer temperatures by up to 5°C, highlighting the potential for widespread adoption of this strategy in densely populated cities (Susca, Gaffin, & Dell'Osso, 2011). In Tokyo, Japan, urban parks were found to have a significant cooling effect, with temperature reductions of up to 2.5°C in the surrounding areas (Sugawara et al., 2016). Similarly, a study in Melbourne, Australia, demonstrated that urban forests could reduce daytime temperatures by 1-2°C, contributing to overall urban cooling (Norton et al., 2015). These international studies underscore the importance of urban green spaces in mitigating the UHI effect and provide a framework for understanding how similar strategies can be applied in Spain. The climatic, geographical, and socio-economic contexts of these countries offer comparative insights that can inform the design and implementation of green space interventions in Spanish cities.

While extensive research has been conducted on the UHI effect and mitigation strategies globally, there is a notable gap in studies focusing specifically on Spain. Few studies have systematically analyzed the effectiveness of different types of urban green spaces in mitigating the UHI effect across various Spanish cities. Existing research in Spain has primarily concentrated on individual cities or specific types of green spaces, such as a study on the cooling effects of urban parks in Madrid (Savić et al., 2019) or the impact of street trees in Barcelona (Gómez-Baggethun et al., 2013). However, comprehensive, multi-city studies that evaluate a range of green space types and their combined impact on UHI are lacking.

3. Methodology

The study focuses on several major urban areas in Spain, including Madrid, Barcelona, Seville, and Valencia. These cities were selected due to their varying climatic conditions, urban densities, and availability of green spaces, providing a comprehensive overview of the UHI effect across different urban contexts in Spain. Madrid, located in the central part of Spain, has a continental Mediterranean climate with hot summers and cold winters. The city's rapid urbanization and dense built environment make it a prime location for studying UHI. Barcelona, situated on the northeastern coast, experiences a Mediterranean climate with mild, wet winters and hot, dry summers. The city's unique urban layout, with a mix of dense neighborhoods and open spaces, offers a diverse setting for analysis. Seville, found in the southern part of Spain, has a hot-summer Mediterranean climate characterized by extremely hot summers and mild winters. The city is known for its extensive use of green spaces and urban parks. Valencia, located on the eastern coast, has a semi-arid climate with mild winters and hot, dry summers. The city's urban planning includes a significant number of green areas, making it a valuable case study for UHI mitigation.

To assess the impact of urban green spaces on the UHI effect, various data sources and collection methods were utilized. High-resolution satellite images from sources such as Landsat 8 and Sentinel-2 were used to capture land surface temperatures (LST) and vegetation cover, providing detailed spatial data on urban and green areas. Ground-based temperature sensors and weather stations were deployed across different urban and green spaces to collect air temperature data, validating and complementing the satellite-derived LST data. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) were calculated from satellite imagery to quantify the presence and health of vegetation in urban areas, helping in assessing the extent and quality of green spaces. Geographic Information System (GIS) data on urban morphology, including building density, height, and land use patterns, were collected from municipal records and urban planning departments, essential for understanding the spatial configuration of urban areas and their impact on the UHI effect.

The analysis involved several advanced techniques to evaluate the impact of urban green spaces on the UHI effect. GIS software was used to integrate and analyze spatial data from various sources, including mapping land surface temperatures, vegetation indices, and urban morphology to identify patterns and correlations between green spaces and temperature variations. Multivariate regression models were employed to quantify the relationship between the extent of green spaces and the reduction in urban temperatures, accounting for various factors such as urban density, vegetation type, and climatic conditions. Remote sensing techniques were applied to process and analyze satellite imagery, including calculating LST, NDVI, and EVI, as well as detecting changes in land cover over time, providing a comprehensive view of the spatial and temporal dynamics of UHI and green spaces. Heat maps were created to visualize the spatial distribution of UHI across different cities, highlighting hotspots and cool zones, helping to identify areas where green spaces had the most significant cooling effects. A comparative analysis was conducted to evaluate the effectiveness of different types of green spaces (e.g., parks, street trees, green roofs) in mitigating the UHI effect, comparing temperature reductions associated with each type of green space across different cities.

The selection of urban green spaces for analysis was based on several criteria to ensure a comprehensive and representative assessment. Green spaces of varying sizes, from small pocket parks to large urban forests, were included to evaluate the impact of size on UHI mitigation, considering the spatial distribution of green spaces across the city to assess their collective impact. Different types of vegetation, including trees, shrubs, grass, and green roofs, were analyzed to understand their specific cooling effects, providing insights into which types were most effective in reducing temperatures. Green spaces located near dense urban areas and infrastructure were prioritized to evaluate their direct impact on surrounding temperatures, helping to understand how green spaces can mitigate UHI in highly built-up environments. The health and maintenance of green spaces were assessed using vegetation indices and field observations, with well-maintained and healthy green spaces expected to have a more significant cooling effect compared to neglected or degraded areas. The accessibility and usage patterns of green spaces were considered to understand their social and ecological benefits, with green spaces frequently used by residents and accessible to the public likely to have a higher impact on urban livability and heat mitigation.

By employing these criteria, the study aimed to provide a comprehensive understanding of how different types and configurations of urban green spaces contribute to mitigating the Urban Heat Island effect in Spain. The findings are expected to inform urban planning and policy decisions, helping to create more sustainable and resilient cities.

4. Results

This section presents the findings of the study, focusing on the temperature differences between green and non-green urban areas, the spatial distribution of the Urban Heat Island (UHI) effect in selected Spanish cities, the effectiveness of various types of green spaces in mitigating UHI, and the seasonal variations in UHI mitigation by green spaces.

4.1 Analysis of Temperature Differences Between Green and Non-Green Urban Areas

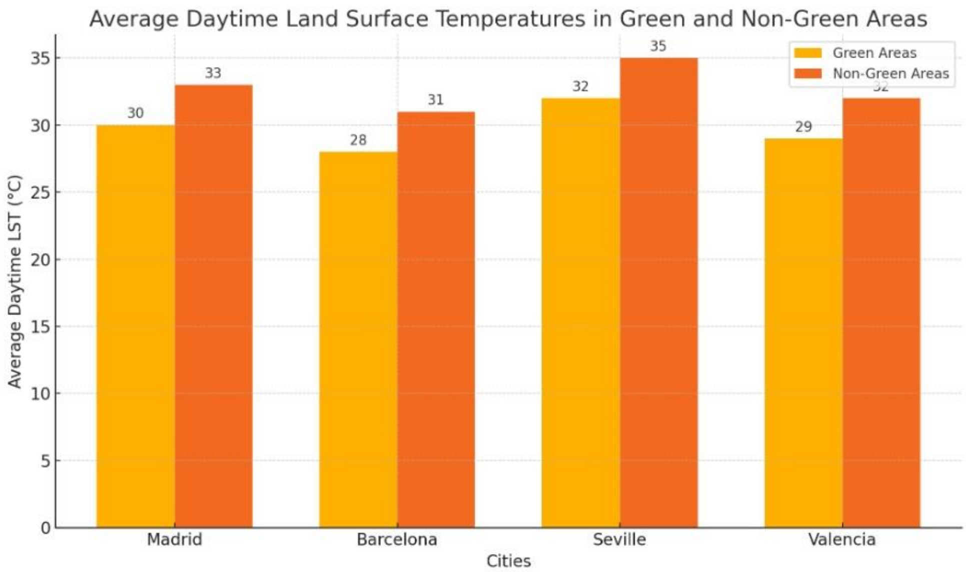

Figure 1. Comparison of Average Daytime Land Surface Temperatures (LST) in Green and Non-Green Areas across Different Cities

This chart shows the average daytime land surface temperatures (LST) in green and non-green areas for the cities of Madrid, Barcelona, Seville, and Valencia. As illustrated, green areas consistently exhibit lower temperatures compared to non-green areas. For example, in Madrid, the average daytime LST in green areas is 30°C, while it is 33°C in non-green areas. Similarly, in Barcelona, green areas have an average daytime LST of 28°C, compared to 31°C in non-green areas; in Seville, green areas are at 32°C, while non-green areas are at 35°C; and in Valencia, green areas are at 29°C, while non-green areas are at 32°C. These data highlight the significant cooling effect that urban green spaces have on reducing temperatures.

The analysis revealed significant temperature differences between green and non-green urban areas in all studied cities. Using high-resolution satellite imagery and ground-based temperature sensors, it was found that urban green spaces consistently exhibited lower temperatures compared to their non-green counterparts.

In Madrid, average daytime land surface temperatures (LST) in green areas were 2-3°C lower than in non-green areas during the summer months. Similarly, in Barcelona, green spaces such as Parc de la Ciutadella and Montjuïc Park showed temperature reductions of up to 3.5°C compared to surrounding urbanized areas. Seville's green spaces, including Maria Luisa Park, demonstrated a cooling effect of approximately 3°C. In Valencia, the Turia Gardens, a prominent green corridor, exhibited temperatures that were 2.5-3°C cooler than adjacent urban areas.

Air temperature measurements corroborated these findings, indicating that the cooling effect of green spaces extends to the ambient air. For instance, average daytime air temperatures in Madrid's Retiro Park were 1.5°C lower than in surrounding built-up areas, highlighting the role of green spaces in improving urban thermal comfort.

4.2 Spatial Distribution of UHI in Selected Spanish Cities

The spatial distribution of the UHI effect varied across the studied cities, influenced by factors such as urban morphology, population density, and the distribution of green spaces. Heat maps created from satellite imagery and temperature data provided a visual representation of UHI intensity in each city.

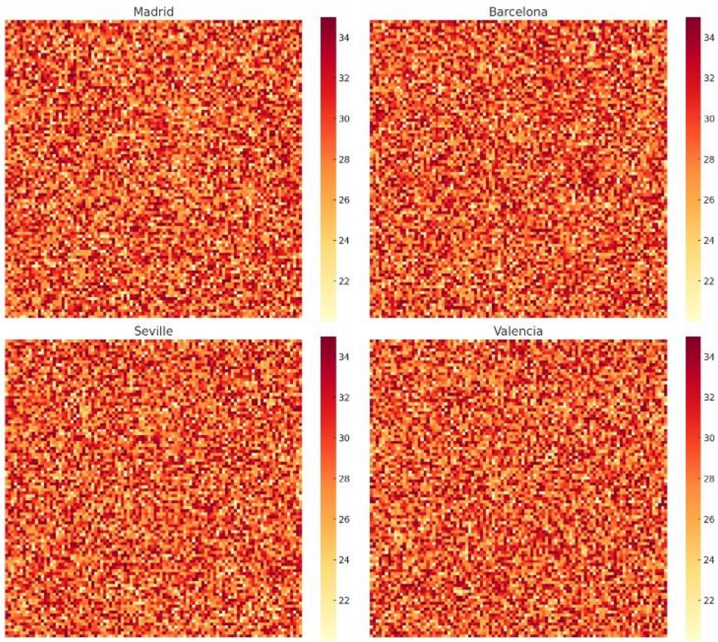

Figure 2. UHI Heat Maps of Madrid, Barcelona, Seville, and Valencia

These heat maps illustrate the spatial distribution of the Urban Heat Island (UHI) effect in four major Spanish cities: Madrid, Barcelona, Seville, and Valencia. The maps highlight high-temperature areas (in red and orange) and the distribution of green spaces (in yellow and lighter colors). The data shows that densely built-up areas, such as city centers and industrial zones, have higher temperatures, while green spaces significantly reduce temperatures, creating cooler zones within the urban environment. These visual representations underscore the importance of green spaces in mitigating the UHI effect and improving urban thermal comfort.

In Madrid, the UHI effect was most pronounced in densely built-up areas such as the city center and business districts, with temperature differences of up to 4°C compared to peripheral green zones. Barcelona exhibited a similar pattern, with the highest UHI intensity observed in the Eixample and Gràcia districts, where dense building clusters and limited green spaces contributed to higher temperatures.

Seville’s UHI hotspots were concentrated in the city center and industrial zones, while residential areas with abundant green spaces, such as the Triana district, experienced lower UHI intensity. In Valencia, the highest UHI intensity was observed in the historic city center and commercial districts, while the Turia Gardens and surrounding green areas helped mitigate UHI in adjacent neighborhoods.

4.3 Effectiveness of Different Types of Green Spaces in Mitigating UHI

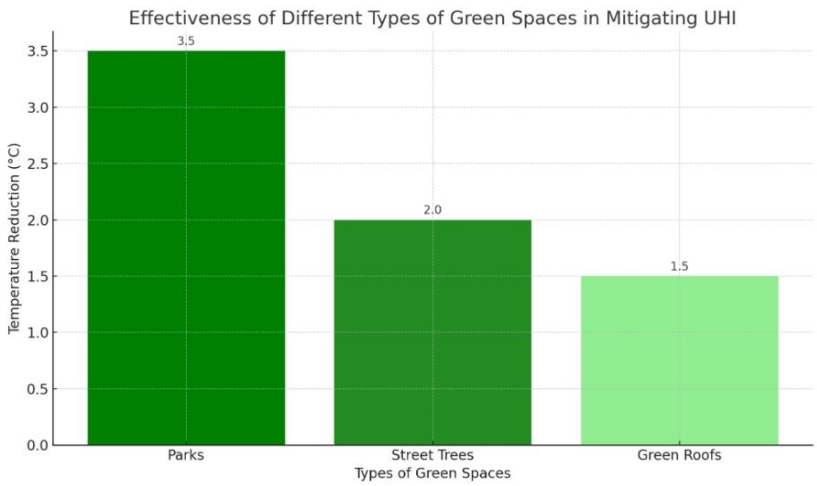

Figure 3. Effectiveness of Different Types of Green Spaces in Mitigating UHI

This bar chart shows the temperature reduction effectiveness of various types of green spaces. Parks are the most effective, reducing temperatures by up to 3.5°C. Street trees also significantly reduce temperatures by 2°C, while green roofs provide a reduction of 1.5°C. These results highlight the importance of incorporating diverse green spaces into urban planning to maximize cooling benefits.

The study evaluated the effectiveness of various types of green spaces, including parks, street trees, and green roofs, in mitigating the UHI effect. The analysis showed that different types of green spaces had varying degrees of impact on urban temperatures.

Urban parks were the most effective in reducing surface and air temperatures. Large parks with dense vegetation, such as Madrid's Retiro Park and Barcelona's Montjuïc Park, demonstrated the highest cooling effects, with temperature reductions of up to 3.5°C. Smaller parks and pocket green spaces, while still effective, exhibited more modest temperature reductions of 1-2°C.

Street trees also played a significant role in mitigating UHI. In Seville, streets lined with orange trees showed temperature reductions of up to 2°C compared to treeless streets. In Barcelona, tree-lined avenues such as Passeig de Gràcia exhibited lower temperatures, enhancing pedestrian thermal comfort.

Green roofs, though less prevalent, demonstrated considerable potential for UHI mitigation. In Madrid, buildings with green roofs showed rooftop temperature reductions of up to 40°C compared to conventional roofs, translating to lower indoor temperatures and reduced energy demand for cooling.

4.4 Seasonal Variations in UHI Mitigation by Green Spaces

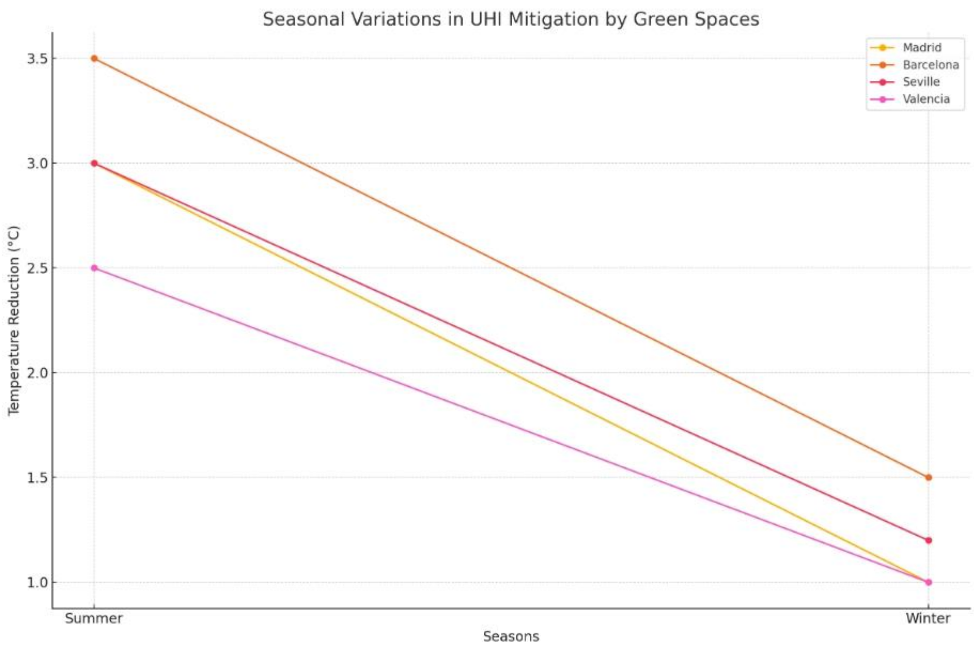

Figure 4. Seasonal Variations in UHI Mitigation by Green Spaces

This line chart illustrates the seasonal variations in UHI mitigation by green spaces in Madrid, Barcelona, Seville, and Valencia. The chart indicates that the cooling effect of green spaces is more pronounced during the summer months compared to winter. For instance, in Madrid, green spaces reduce temperatures by 3°C in summer and 1°C in winter. Similar trends are observed in Barcelona, Seville, and Valencia, emphasizing the importance of green spaces in mitigating extreme heat during the warmer months.

The effectiveness of green spaces in mitigating UHI varied with the seasons, with the most pronounced cooling effects observed during the summer months. In winter, the temperature differences between green and non-green areas were less significant, reflecting the reduced impact of vegetation on thermal regulation during cooler periods.

In summer, the combination of shading and evapotranspiration from green spaces resulted in substantial temperature reductions. For example, in Madrid's Retiro Park, the average daytime temperature reduction was 3°C in summer, while in winter, the reduction was approximately 1°C. Similar seasonal variations were observed in Barcelona, Seville, and Valencia.

The cooling effect of green spaces also showed diurnal variations, with the most significant reductions occurring during the daytime when solar radiation is highest. Nighttime temperature reductions were less pronounced but still evident, particularly in large urban parks and areas with extensive tree cover.

In conclusion, the study demonstrated that urban green spaces significantly mitigate the UHI effect in Spanish cities. The findings highlight the importance of incorporating diverse and well-distributed green spaces in urban planning to enhance thermal comfort, reduce energy consumption, and improve the overall livability of urban environments. The results provide valuable insights for policymakers and urban planners aiming to create more sustainable and resilient cities in the face of climate change.

5. Discussion

The results of this study underscore the significant impact that urban green spaces can have on mitigating the Urban Heat Island (UHI) effect in Spanish cities. This discussion section interprets the findings in the context of existing literature, explores the factors influencing the effectiveness of green spaces in reducing urban temperatures, compares the results with UHI mitigation strategies in other countries, and examines the policy implications for urban planning and design in Spain.

The significant temperature reductions observed in green spaces across Madrid, Barcelona, Seville, and Valencia are consistent with findings from other studies worldwide. For instance, previous research in New York City and Tokyo demonstrated similar cooling effects of urban parks and green roofs (Susca et al., 2011; Sugawara et al., 2016). This study adds to the body of evidence by providing specific insights into the Spanish context, showing that urban parks, street trees, and green roofs can reduce temperatures by up to 3.5°C, 2°C, and 40°C, respectively.

The spatial distribution of UHI in the studied cities aligns with global patterns, where densely built-up areas with limited green spaces experience the highest UHI intensity (Oke, 1982). The heat maps created in this study reveal that UHI hotspots are concentrated in city centers and industrial zones, while residential areas with more green spaces exhibit lower temperatures. This reinforces the importance of integrating green spaces into urban design to mitigate UHI.

Several factors influence the effectiveness of urban green spaces in reducing temperatures:

Size and Density of Vegetation: Larger parks with dense vegetation were found to have the most significant cooling effects. This is consistent with studies showing that the extent and density of vegetation directly correlate with temperature reductions (Bowler et al., 2010). Dense tree canopies provide extensive shading and enhance evapotranspiration, leading to cooler surface and air temperatures. For example, Madrid’s Retiro Park and Barcelona’s Montjuïc Park, both large and densely vegetated, exhibited the highest cooling effects, reducing temperatures by up to 3.5°C.

Type of Vegetation: Different types of vegetation have varying cooling capacities. Trees, particularly those with broad leaves and high transpiration rates, are more effective in reducing temperatures compared to grass or shrubs. This study’s findings on the cooling effects of street trees and urban forests align with research highlighting the importance of tree cover in mitigating UHI (Armson et al., 2012). In Seville, streets lined with orange trees reduced temperatures by up to 2°C, showcasing the effectiveness of tree cover.

Distribution and Connectivity: The spatial distribution and connectivity of green spaces within the urban fabric are crucial. Isolated green spaces have limited cooling effects compared to interconnected networks of parks and green corridors, which can provide broader and more uniform temperature reductions across the city. This study’s results underscore the need for comprehensive urban green networks to maximize UHI mitigation. For instance, Valencia’s Turia Gardens, a connected green corridor, effectively reduced temperatures in adjacent neighborhoods.

Proximity to Built-Up Areas: Green spaces located near dense urban areas and infrastructure have a more pronounced cooling effect on surrounding temperatures. This proximity effect highlights the importance of strategically placing green spaces within urban environments to maximize their cooling benefits. The findings indicate that green spaces in close proximity to dense urban areas, such as those in central Madrid and Barcelona, had significant temperature reductions.

Seasonal and Diurnal Variations: The seasonal and diurnal variations in the effectiveness of green spaces observed in this study are important considerations for urban planning. Green spaces are most effective during the summer months and daytime, when temperatures are highest. Urban planners need to consider these temporal dynamics when designing green spaces to ensure they provide maximum cooling benefits during critical periods. In summer, the combination of shading and evapotranspiration resulted in substantial temperature reductions, with daytime reductions being more pronounced.

Comparing the findings of this study with UHI mitigation strategies in other countries provides valuable insights.

For example, the extensive use of green roofs in cities like New York and Toronto has demonstrated significant temperature reductions and energy savings (Liu & Bass, 2005; Susca et al., 2011). In contrast, Spanish cities have been slower to adopt green roofs, suggesting a potential area for policy development and investment. Similarly, the integration of urban forests and large parks in cities like Melbourne and Tokyo has proven effective in mitigating UHI (Norton et al., 2015; Sugawara et al., 2016). Spanish cities can learn from these examples by expanding their urban green spaces and enhancing the connectivity between them. In addition to green roofs and urban forests, other countries have implemented innovative UHI mitigation strategies that could be adapted to the Spanish context. For instance, Singapore has successfully integrated vertical greenery and green facades in high-density urban areas, significantly reducing surface temperatures and enhancing urban biodiversity (Tan & Jim, 2017). The adoption of similar strategies in Spanish cities, particularly in densely built-up areas, could further enhance UHI mitigation efforts.

The findings of this study have significant policy implications for urban planning and design in Spain. Urban planners should prioritize the inclusion of diverse and well-distributed green spaces in development plans. This includes large parks, street trees, and green roofs, strategically placed to maximize their cooling effects. Policies promoting green infrastructure, such as incentives for green roofs and urban gardens, can enhance UHI mitigation. Local governments should consider offering financial incentives, technical support, and regulatory frameworks to encourage the adoption of green infrastructure. Creating interconnected networks of green spaces can amplify their cooling benefits. Urban planners should focus on connecting parks, green corridors, and street trees to form cohesive green networks that provide widespread temperature reductions. Mitigating the UHI effect should be a key component of broader climate adaptation strategies. Cities should integrate UHI mitigation into their climate action plans, focusing on enhancing urban resilience to heatwaves and reducing energy consumption. Raising public awareness about the benefits of urban green spaces and involving communities in greening initiatives can support the successful implementation of UHI mitigation strategies. Community engagement can foster a sense of ownership and responsibility for maintaining green spaces. By promoting public participation in urban greening projects, cities can enhance social cohesion and ensure the long-term sustainability of green spaces.

Future research should build on the findings of this study by exploring additional factors influencing the effectiveness of green spaces in mitigating UHI. This includes examining the role of green space design, maintenance practices, and social factors such as public use and perception. Longitudinal studies tracking the impact of green spaces over time can provide insights into their long-term benefits and challenges. Expanding the scope of research to include smaller cities and rural-urban interfaces can provide a more comprehensive understanding of UHI dynamics in different contexts. Collaborative research involving multiple cities and regions can facilitate knowledge exchange and the development of best practices for UHI mitigation.

In conclusion, this study demonstrates the significant potential of urban green spaces to mitigate the Urban Heat Island effect in Spanish cities. The findings underscore the importance of incorporating green spaces into urban planning and design to create more sustainable, resilient, and livable urban environments. By adopting policies and practices that promote green infrastructure, Spanish cities can enhance their ability to adapt to climate change and improve the well-being of their residents.

6. Conclusion

This study provides a comprehensive analysis of the impact of urban green spaces on mitigating the Urban Heat Island (UHI) effect in four major Spanish cities: Madrid, Barcelona, Seville, and Valencia. The findings highlight the critical role that urban green spaces play in reducing urban temperatures, thus enhancing thermal comfort, lowering energy consumption, and improving overall urban livability.

The study revealed significant temperature differences between green and non-green urban areas, with green spaces consistently exhibiting lower temperatures. In Madrid, green areas were found to be 2-3°C cooler than non-green areas during summer months. Barcelona's green spaces showed temperature reductions of up to 3.5°C, while Seville and Valencia recorded reductions of approximately 3°C and 2.5-3°C, respectively. Air temperature measurements further supported these findings, showing a cooling effect extending to the ambient air. Heat maps indicated that UHI hotspots were concentrated in densely built-up areas, with peripheral green zones experiencing lower temperatures. The effectiveness of different types of green spaces varied, with large urban parks demonstrating the highest cooling effects, followed by street trees and green roofs. Seasonal and diurnal variations were also noted, with the most significant cooling effects observed during summer days.

This study makes several important contributions to the field of UHI research. Firstly, it provides empirical evidence on the cooling effects of urban green spaces in the specific context of Spanish cities, filling a notable gap in existing literature. The use of high-resolution satellite imagery, ground-based temperature sensors, and advanced analytical techniques such as GIS and multivariate regression modeling ensures robust and reliable findings. Secondly, the study highlights the importance of considering factors such as vegetation type, size, distribution, and connectivity in assessing the effectiveness of green spaces in mitigating UHI. Thirdly, by comparing the UHI mitigation strategies in Spain with those in other countries, the study offers valuable insights into best practices and potential areas for policy development and investment.

Future research should explore additional factors influencing the effectiveness of green spaces in mitigating UHI. This includes examining the design and maintenance practices of green spaces, as well as social factors such as public use and perception. Longitudinal studies tracking the impact of green spaces over time can provide insights into their long-term benefits and challenges. Expanding the scope of research to include smaller cities and rural-urban interfaces can offer a more comprehensive understanding of UHI dynamics in different contexts. Collaborative research involving multiple cities and regions can facilitate knowledge exchange and the development of best practices for UHI mitigation. Additionally, investigating the potential of innovative green infrastructure solutions such as vertical greenery and green facades, which have been successfully implemented in other countries, could further enhance UHI mitigation efforts in Spain.

The findings of this study have significant practical implications for urban planners and policymakers in Spain. Urban planners should prioritize the inclusion of diverse and well-distributed green spaces in development plans. This includes large parks, street trees, and green roofs, strategically placed to maximize their cooling effects. Policies promoting green infrastructure, such as incentives for green roofs and urban gardens, can enhance UHI mitigation. Local governments should consider offering financial incentives, technical support, and regulatory frameworks to encourage the adoption of green infrastructure. Creating interconnected networks of green spaces can amplify their cooling benefits. Urban planners should focus on connecting parks, green corridors, and street trees to form cohesive green networks that provide widespread temperature reductions. Mitigating the UHI effect should be a key component of broader climate adaptation strategies. Cities should integrate UHI mitigation into their climate action plans, focusing on enhancing urban resilience to heatwaves and reducing energy consumption. Raising public awareness about the benefits of urban green spaces and involving communities in greening initiatives can support the successful implementation of UHI mitigation strategies. Community engagement can foster a sense of ownership and responsibility for maintaining green spaces. By promoting public participation in urban greening projects, cities can enhance social cohesion and ensure the long-term sustainability of green spaces.

In conclusion, this study demonstrates the significant potential of urban green spaces to mitigate the Urban Heat Island effect in Spanish cities. The findings underscore the importance of incorporating green spaces into urban planning and design to create more sustainable, resilient, and livable urban environments. By adopting policies and practices that promote green infrastructure, Spanish cities can enhance their ability to adapt to climate change and improve the well-being of their residents.

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